UNITED TECHNOLOGIES
PRATT&WHITNEY

P.O. Box 109600
West Palm Beach, FL 33410-9600
(407) 796-2000

Government Engines & Space Propulsion

(2)



17 December 1992



Office of Navy Research
Scientific Officer
Attn: Dr. A. K. Vasudevan, Code 1222
800 N. Quincy Street
Arlington, Va 22217-5000

Contract No. N00014-91-C-0124
Item No. 0002, Sequence No. A001

Subject: Submittal of the Progress Report, FR21998-14

Gentlemen:

In accordance with the applicable requirements of the contract, we herewith submit one (1) copy of the subject report.

Very truly yours,

UNITED TECHNOLOGIES CORPORATION
Pratt & Whitney

Margaret B Hall
Margaret B. Hall
Contract Data Coordinator





cc: With Enclosures

Director, Naval Research, Code 2627
DPRO
Defense Technical Information Center (2 copies)
Dr. K. Sadananda

# FATIGUE IN SINGLE CRYSTAL NICKEL SUPERALLOYS

**Technical Progress Report**

**Daniel P. DeLuca**
**Principal Investigator**

**Charles Annis**
**Program Manager**

**UNITED TECHNOLOGIES PRATT&WHITNEY**
**P.O. Box 109600**
**West Palm Beach, FL 33410-9600**
**(407)796-6565**
**Government Engines and Space Propulsion**

**15 December, 1992**

**Period of performance**
**16 November 1992 through 15 December 1992**

**Contract N00014-91-C-0124**

Prepared for:
**Dr. A. K. Vasudevan, Scientific Officer**
**Code 1222**

**Office of Naval Research**
**Department of the Navy**
**800 N. Quincy Street**
**Arlington, Va 22217-5000**

## I. Introduction and Program Objective

This program investigates the seemingly unusual behavior of single crystal airfoil materials. The fatigue initiation processes in single crystal (SC) materials are significantly more complicated and involved than fatigue initiation and subsequent behavior of a (single) macrocrack in conventional, isotropic, materials. To understand these differences it is helpful to review the evolution of high temperature airfoils.

### Characteristics of Single Crystal Materials

Modern gas turbine flight propulsion systems employ single crystal materials for turbine airfoil applications because of their superior performance in resisting creep, oxidation, and thermal mechanical fatigue (TMF). These properties have been achieved by composition and alloying, of course, but also by appropriate crystal orientation and associated anisotropy.

Early aeroengine turbine blade and vane materials were conventionally cast, equiaxed alloys, such as IN100 and Rene'80. This changed in the late 1960s with the introduction of directionally-solidified (DS) MAR-M200 + Hf airfoils. The DS process produces a <001> crystallographic orientation, which in superalloys exhibits excellent strain controlled fatigue resistance due to its low elastic modulus. The absence of transverse grain boundaries, a 60% reduction in longitudinal modulus compared with equiaxed grains, and its corresponding improved resistance to thermal fatigue and creep, permitted significant increases in allowable metal temperatures and blade stresses. Still further progress was achieved in the mid-1970s with the development of single crystal airfoils[1].

The first such material, PWA 1480, has a considerably simpler composition than preceding cast nickel blade alloys because, in the absence of grain boundaries, no grain boundary strengthening elements are required. Deleting these grain boundary strengtheners, which are also melting point depressants, increased the incipient melt temperature. This, in turn, allowed nearly complete $\gamma'$ solutioning during heat treatment and thus a reduction in dendritic segregation. The absence of grain boundaries, the opportunity for full solution heat treatment, and the minimal post-heat treat dendritic segregation, result in significantly improved properties as compared with conventionally cast or directionally solidified alloys. Single crystal castings also share with DS alloys the <001> crystal orientation, along with the benefits of the resulting low modulus in the longitudinal direction.

Pratt & Whitney has developed numerous single crystal materials. Like most, PWA 1480 and PWA 1484 are $\gamma'$ strengthened cast mono grain nickel superalloys based on the Ni-Cr-Al system. The bulk of the microstructure consists of approximately 60% by volume of cuboidal $\gamma'$ precipitates in a $\gamma$ matrix. The precipitate ranges from 0.35 to 0.5 microns and is an ordered Face Centered Cubic (FCC) nickel aluminide compound. The macrostructure of these materials

---

[1] Gell, M., D. N. Duhl, and A. F. Giamei, 1980, "The Development of Single Crystal Superalloy Turbine Blades," *Superalloys* 1980, proceedings of the Fourth International Symposium on Superalloys, American Society for Metals, Metals Park, Ohio, pp. 205-214.

is characterized by parallel continuous primary dendrites spanning the casting without interruption in the direction of solidification. Secondary dendrite arms (perpendicular to solidification) define the interdendritic spacing. Solidification for both primary and secondary dendrite arms proceeds in $<001>$ type crystallographic directions. Undissolved eutectic pools and associated microporosity reside throughout the interdendritic areas. These features act as microstuctural discontinuities, and often exert a controlling influence on the fatigue initiation behavior of the alloy. Also, since the eutectics are structurally dissimilar from the surrounding matrix their fracture characteristics will differ.

**Single Crystal Fatigue**

The fatigue process in single crystal airfoil materials is a remarkably complex and interesting process. In cast single crystal nickel alloys, two basic fracture modes, crystallographic and non-crystallographic, are seen in combination. They occur in varying proportions depending upon temperature and stress state. Crystallographic orientation with respect to applied load also affects the proportion of each and influences the specific crystallographic planes and slip directions involved. Mixed mode fracture is observed under monotonic as well as cyclic conditions.

Single crystal turbine blades are cast such that the radial axis of the component is essentially coincident with the $<001>$ crystallographic direction which is the direction of solidification. Crystallographic fracture is usually seen as either octahedral along multiple (111) planes or under certain circumstances as (001) cleavage along cubic planes.

Non-crystallographic fracture is also observed. Low temperatures favor crystallographic fracture. At higher temperatures, in the 427°C range, small amounts of non-crystallographic propagation have the appearance of transgranular fatigue in a related fine grain equiaxed alloy. Under some conditions, this propagation changes almost immediately to the highly crystallographic mode along (111) shear planes, frequently exhibiting prominent striations emanating from the fatigue origin and continuing to failure in overstress. Under other conditions the non-crystallographic behavior can continue until tensile failure occurs. At intermediate temperatures (around 760C) non-crystallographic propagation is more pronounced and may continue until tensile overload along (111) planes occurs, or may transition to subcritical crystallographic propagation. At 982°C, propagation is almost entirely noncrystallographic, similar to transgranular propagation in a polycrystal.

**Damage Catalogue**

This program will identify and compile descriptions of the fracture morphologies observed in SC airfoil materials under various combinations of temperature and stress associated with advanced Navy aeropropulsion systems. We will suggest fatigue mechanisms for these morphologies and catalogue them as unique damage *states*. Most testing will be accomplished under ancillary funding, and therefore be available to this effort at not cost. The work is organized into four tasks, which are described in the following paragraphs.

## II. Program Organization

The program is structured into four tasks, three technical and one reporting. The individual tasks are outlined here.

### Task 100 - Micromechanical Characterization

This task will define the mechanisms of damage accumulation for the various types of fracture observed in single crystal alloys. These fracture characteristics will be used to establish a series of Damage States which represent the fatigue damage process. The basis for this investigation will be detailed fractographic assessment of failed laboratory specimens generated in concurrent programs. Emphasis will be on specifically identifying the micromechanical damage mechanisms, relating them to a damage state, and determining the conditions required to transition to an alternate state.

### Task 200 - Analytical Parameter Development

This task will extend current methods of fatigue and fracture mechanics analysis to account for microstructural complexities inherent in single crystal alloys. This will be accomplished through the development of flexible correlative parameters which can be used to evaluate the crack growth characteristics of a particular damage state. The proposed analyses will consider the finite element and the hybrid Surface-Integral and Finite Element (SAFE) methods to describe the micromechanics of crack propagation.

### Task 300 - Probabilistic Modeling

This task will model the accumulation of fatigue damage in single crystal alloys as a Markov process. The probabilities of damage progressing between the damage states defined in Task 100 will be evaluated for input into the Markov model. The relationship between these transition probabilities and fatigue life will then be exploited to establish a model with comprehensive life predictive capabilities.

### Task 400 - Reporting

Running concurrently with the analytical portions of the program, this task will inform the Navy Program Manager and Contracting Officer of the technical and fiscal status of the program through R&D status reports.

## III. Technical Progress

Our research into the micromechanics of single crystal fracture in this program has been paralleled by a USAF specimen test program. We feel we now possess an improved understanding of the relationship between microstructure and intermediate temperature fracture behavior.

Historically the primary consideration in turbine blade alloy development has been to achieve high temperature strength, creep capability and oxidation erosion resistance. Significant advancements have been made in meeting these needs by the development of optimum alloy chemistry microstructure and casting form (i.e., equiaxed, columnar grain, single crystal). The development of the

universally employed fine uniform cuboidal $\gamma'$ precipitate structure has been fundamental to meeting this end. Microstructural parameters for $\gamma'$ size, shape, volume fraction and $\gamma - \gamma'$ misfit evolved as they are today to achieve an optimum balance between high temperature strength and resistance to creep. These high temperature (870 C and above) qualities are dictated by the environment in which the airfoil portion of a gas turbine blade must operate.

The attachment area of a turbine blade however operates at a lower temperature and presents a differing set of requirements. Current trends in gas turbine technology emphasize damage tolerance (ie., resistance to crack propagation). Microstructural parameters developed for high temperature capability are not optimum for crack growth resistance.

We have investigated the micromechanics of fracture in the $\gamma'$ strengthened anisotropic superalloys and have observed fatigue crack growth to be highly dependant on $\gamma'$ precipitate morphology.

We have observed that at elevated temperatures (427°C and above) the minimum stress intensity necessary to propagate a crack increases with increasing temperature up to about 815°C. This coincides with the tendency for $\gamma'$ strengthened superalloys to exhibit an increase in the critical resolved shear stress (CRSS) and consequently yield strength with increasing temperature.

This condition is attributed to a strengthening mechanism known as thermally activated cube cross slip where mobile dislocations cross slip from octahedral planes to cube planes. They then form sessile obstacles (cross slipped dislocation segments inhibiting further dislocation glide) acting as barriers to further dislocation cutting of the precipitates thereby increasing yield strength. Since the cross slip process is thermally activated the strengthening contribution due to the cube cross-slip process increases with increasing temperature.

The dislocation dynamics that control deformation determine the micromechanisms of fracture as well. The resolved stress intensity parameter $K_{rss}$ is the fracture parameter that is analogous to the deformation parameter CRSS and is defined as the limiting value of the resolved shear stress as r, the distance to the crack tip approaches zero.

The degree to which a precipitate resists dislocation cutting determines the microscopic fracture mode and subsequent crack growth rate behavior. If the resolved shear stress intensity ($K_{RSS}$) falls below a critical value required to force dislocation penetration of the precipitate, failure is confined to the matrix phase.

Once a dislocation enters the precipitate, dislocation dynamics within the ordered atomic structure (the superlattice) determine CRSS.

At approximately 427°C thermally activated cube cross slip becomes a viable mode of deformation. Cross slipped dislocation segments begin to fault cube planes at this point in addition to octahedral plane faulting. Fracture at this point appears non-crystallographic. Superlattice dislocation dynamics are dictated by quantum mechanics. The relative Antiphase Boundary Energy (APBE) of the cube versus octahedral planes is a function of superlattice composition; the composition of the precipitate then becomes fundamental in controlling the

tendency for cube cross slip (the strengthening mechanism that resists slip deformation of the precipitate). We hypothesize that this affects microscopic fracture mode and hence fracture resistance. To summarize, the elemental partitioning to the $\gamma'$ phase during the precipitation cycle affects the chemical composition and hence superlattice dislocation dynamics.

The degree to which a strengthening mechanism inhibits dislocation mobility determines the resistance to fracture.

The character of the dislocation motion determines the microscopic fracture mode and therefore the growth rate.

## IV. Current Problems

No technical problems have been encountered during the reporting period.

**REPORT DOCUMENTATION PAGE**

1. Report No.: FR2198-14

2.

3. Recipient's Accession No.

4. Title and Subtitle:
FATIGUE IN SINGLE CRYSTAL NICKEL SUPERALLOYS
Technical Progress Report

5. Report Date: 15 December, 1992

6.

7. Author(s): Charles Annis

8. Performing Organization Rept. No.: FR2198-14

9. Performing Organization Name and Address:
United Technologies
Pratt & Whitney
P. O. Box 109600
West Palm Beach, FL 33410-9600

10. Project/Task/Work Unit No.

11. Contract(C) or Grant(G) No.:
(C) N00014-91-C-0124
(G)

12. Sponsoring Organization Name and Address:
Office of Naval Research
Department of the Navy
800 N. Quincy Street
Arlington, VA 22217-5000

13. Type of Report & Period Covered:
Monthly
11/16/92 - 12/15/92

14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

This program investigates the seemingly unusual behavior of single crystal airfoil materials. The fatigue initiation processes in single crystal (SC) materials are significantly more complicated and involved than fatigue initiation and subsequent behavior of a (single) macrocrack in conventional, isotropic, materials. To understand these differences is the major goal of this project.

17. Document Analysis a. Descriptors

Fatigue, Fracture, Single Crystal, PWA 1480, PWA 1484

b. Identifiers/Open-Ended Terms

c. COSATI Field/Group

18. Availability Statement: Unlimited

19. Security Class (This Report): Unclassified

20. Security Class (This Page)

21. No. of Pages: 6

22. Price